RESONANT ROTATION STATES OF THE JOVIAN AND SATURNIAN SATELLITES. Alexander Stark [1], Hauke Hussmann [1], Gregor Steinbrügge [2], Jürgen Oberst [1,3], Thomas Roatsch [1]. [1] German Aerospace Center (DLR), Institute of Planetary Research (alexander.stark@dlr.de), D-12489 Berlin, Germany; [2] Institute for Geophysics, University of Texas at Austin, Austin, TX 78758, USA; [3] Institute of Geodesy and Geoinformation Science, Technische Universität Berlin, D-10623 Berlin, Germany.

Introduction: Many of the moons of the giant planets are trapped in a 1:1 spin-orbit resonance. Up to now this special rotation state is confirmed by observations for 8 satellites of Jupiter, 15 satellites of Saturn, 15 satellites of Uranus, and 7 satellites of Neptune [1]. These rotation states are a result from the strong tidal torque exerted on the satellites by their central body. However, slight deviations from the resonant state, e.g., physical librations, can provide hints to the interior structure of the satellites. By deriving the resonant rotation states for the satellites, we provide a critical reference to which the actual measurements can be compared. By that the resonant rotation states can contribute to the knowledge on the formation and evolution of moons around the giant planets in our Solar System.

Method: We derive the resonant rotation states from the ephemerides of the satellites. First we obtain the osculating orbital elements of a satellite in an inertial reference frame, i.e., International Celestial Reference Frame (ICRF). Thereby we apply a sampling time step of about 1% of the orbital period and use the complete time interval available in the satellite ephemeris. Then we decompose the signal (time series of one osculating orbital element) in a secular part and a sum of periodic terms

$$x(t) = x_0 + x_1 t + \sum_{i=2}^{n_\mathrm{s}} x_i t^i + \sum_{i=1}^{n_\mathrm{p}} x_i^\mathrm{p} \frac{\sin(\omega_i t + \varphi_i)}{\cos(\omega_i t + \varphi_i)},$$

where $x(t)$ is the signal, t the ephemeris time (TDB), x_i are the parameters of the secular part and $x_i^\mathrm{p}, \omega_i, \varphi_i$ are the amplitude, frequency, and phase of the periodic part, respectively. n_s and n_p denote the number of terms in the secular and periodic part, respectively. The parameters are obtained by an iterative algorithm. At first a Fourier transformation of the signal is performed to identify the frequency and phase of the highest amplitude in the power spectrum. The derived values are then used as initial values within a least-squares fit of the secular and periodic parts. With the obtained fit parameters the identified component is extracted from the original signal and the iteration cycle starts again with the residuals as input signal. The iteration stops when a specified threshold in the residuals RMS is reached or when the requested number of periodic terms n_p is obtained. More details on the frequency mapping approach can be found in [2,3,4].

In order to derive the orientation of the resonant rotation axis we use the parameters obtained from the decomposition of the time series of the orbital inclination i and the longitude of the ascending node Ω. For the resonant rotation state we assume that the satellite occupies Cassini state 1 with zero obliquity. Furthermore, we assume that the free precession period is much smaller than any periods in the orbit orientation variations. With these assumptions the satellite's rotation axis is precisely following the instantaneous orientation of the orbital plane. This assumption is supported by the fact that amplitudes of very short variations of the orbital orientation are typically very small and can be neglected in practice. In some cases where the free precession period is considered to be close to some period of significant orientation variation the derived values can be used as forcing terms in the computation of the satellite's response. Hence, we derive the resonant rotation axis parameters by mapping them to the parameters of the osculating orbital elements

$$\alpha_0 = \Omega_0 + \frac{\pi}{2}, \qquad \alpha_i = \Omega_i\,, \qquad \alpha_i^\mathrm{p} = \Omega_i^\mathrm{p}$$
$$\delta_0 = \frac{\pi}{2} - i_0, \qquad \delta_i = -i_i\,, \qquad \delta_i^\mathrm{p} = -i_i^\mathrm{p}\,.$$

The trigonometric functions $\sin(\omega_i t + \varphi_i)$ and $\cos(\omega_i t + \varphi_i)$ can be directly inferred from the orbital elements.

With the resonant rotation axis we can now compute the longitudinal libration forcing terms. For that we compute the angle λ measured between the direction to the central body and the *x*-axis of the frame aligned with the rotation axis in *z*-direction. By construction of this frame, the vector pointing from the satellite to the central body lies always in the same plane, i.e., the orbital plane. The derived angle λ is comparable to the mean longitude in case the rotation axis is close to the *z*-axis of the inertial frame. The decomposition of λ gives the dynamical prime meridian constant λ_0, resonant rotation rate λ_1, and the forcing amplitudes of the longitudinal libration λ_i^p. Likewise, for the resonant rotation axis the response of the satellite to the forcing is dependent on the free libration period. If this free libration period, which is determined by the moments of inertia of the satellite, is close to some forcing period a resonant enhancement of the response can occur. For the resonant rotation model, we again assume that the free libration period is vanishing and report all forcing terms which are above a specified threshold, e.g., 10 arc sec.

Results: We focus here on the resonant rotation state of Enceladus. Using Cassini Imaging Science Subsystem (ISS) images the Enceladus' physical libration amplitude of about 500 m (at the equator) has been measured [5]. Besides the annual libration (at 1.37 days) the authors have also considered long-period libration terms with periods of 3.88 and 11.05 years, respectively [6]. Our analysis of the libration forcing λ reveals that there are two additional terms with periods of 2.36 and 4.99 years, which have amplitudes of about 100 m (at the equator) (see Figure 1) [7]. This value is larger than the 2σ uncertainty for the annual libration amplitude of 60 m [5]. We argue that these long-period terms can bias the annual libration measurement especially in the case when observations from different epochs are combined in the analysis. Figure 2 depicts the long-period libration with only two periods as used in [5] (black line) and with four periods (blue line).

Conclusion: The resonant rotation states can be used to constrain changes in the rotation which typically last much longer (several decades) than the observational time for the rotation measurement (few years). They provide a critical reference and can be used as operational framework until actual measurements are available.

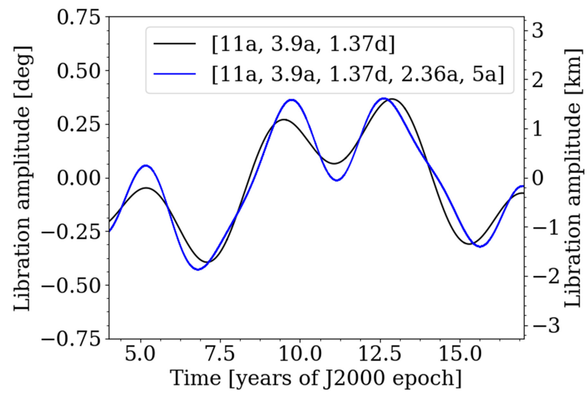

Figure 2: Long-period libration for Enceladus over a full long-term cycle. The black line denotes the terms discussed by [6] and used by [5]. The blue curve represents the long-period libration, which considers all amplitudes larger than 100 m (marked red in Figure 1).

References: **[1]** Archinal et al., 2018, *Celest. Mech. Dyn. Astron.*, 130, 22. **[2]** Stark, et al., 2015. *Celest. Mech. Dyn. Astron.*, 123, 263-277. **[3]** Stark et al., 2017, *European Planetary Science Congress 2017*, Abstract EPSC2017-868-1. **[4]** Stark et al., 2018, *EGU General Assembly Conference*, Abstract EGU2018-10488. **[5]** Thomas, et al., 2016, *Icarus*. 264, 37-47. **[6]** Rambaux, et al., 2010, *GRL*, 37, L04202. **[7]** Giese and Rambaux, 2015, *European Planetary Science Congress* 2015, Abstract EPSC2015-867.

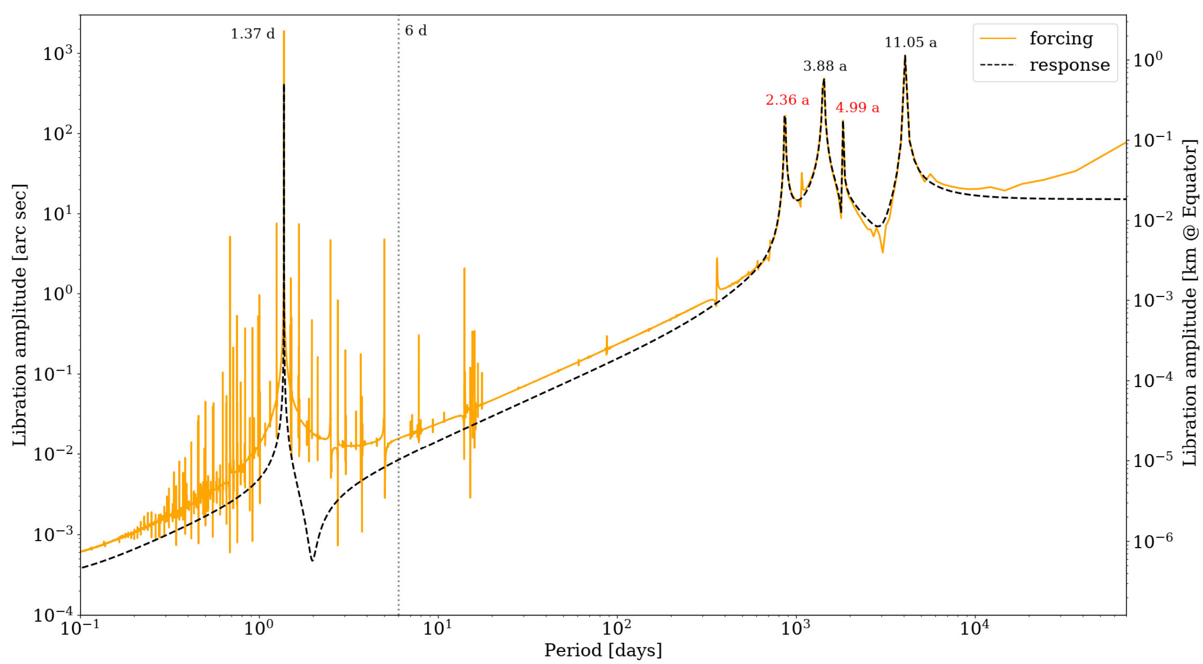

Figure 1: Forcing spectrum (orange line) and librational response (black dashed line) for Enceladus. The response, i.e., physical libration, is obtained by considering forcing terms with amplitudes exceeding 100 m (about 10 arc seconds). The free libration period (vertical dotted line), depending on parameters of interior structure, is adopted to be around 6 days. The amplitude for annual libration (at 1.37 days) is taken from [5] and forcing terms denoted in red were not considered by [5].